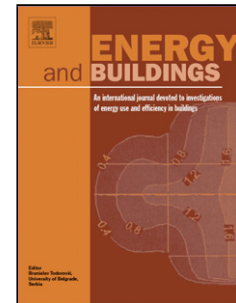


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Author: Babak Raji Martin J. Tenpierik Andy van den Dobbelaar



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Highlights

- For high-rises, optimization of design elements can save up to 40% on energy use.
- The optimum WWR is around 50% for East and West orientations in temperate climates.
- For a DSF building, blinds perform better when placing them outside the cavity.
- A summer operation schedule is preferable for adjustable shadings in cold climates.
- Adding a green roof to a well-insulated roof hardly influences energy consumption.

An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates; a case study in the Netherlands

Babak Raji^{a*}, b.raji@tudelft.nl, Martin J. Tenpierik^a, Andy van den Dobbelsteen^a

^a Delft University of Technology, Delft, The Netherlands

* Corresponding author. PO Box 5043, 2600 GA Delft, The Netherlands. Tel.: +31 6 19999508.

Abstract

The building envelope is the interface between the interior of the building and the outdoor environment. A building's energy consumption to a large extent depends on certain envelope design elements. As a consequence, for achieving high levels of energy-saving in buildings, design measures with high impact should be firstly defined and then optimised. This paper aims at finding energy-saving solutions for the envelope design of high-rise office buildings in temperate climates. For this purpose an existing tall office building is selected as a typical high-rise design in the Netherlands and the energy use prior and after refurbishment is compared through computer simulations with DesignBuilder. A sensitivity analysis in line with a large number of energy performance simulations showed which building envelope parameters have a significant impact on the building's energy consumption; hence need more consideration for improvement. The four measures selected for uplifting the energy performance of the building envelope include glazing type, window-to-wall ratio, sun shading and roof strategies. By taking the base case as a reference and optimising one parameter at each step, this study resulted in a high-performance envelope design that offers a considerable energy-saving by around 42% for total energy use, 64% for heating and 34% for electric lighting.

Keywords: Envelope design strategies, Energy efficiency, High-rise office building, Energy simulation, sensitivity analysis

1. Introduction

During the last decade, international organizations have put considerable effort toward energy-efficiency in buildings as evidenced by EU Energy Efficiency Action Plans for 2020 and 2030 [1,2]. Currently, buildings account for almost 40% of total energy consumption and 36% of greenhouse gas emission in European countries [3]. The largest amount of energy consumption in commercial buildings is for space heating, cooling, ventilation and electric lighting. The building envelope is the interface between the indoor and the outdoor environment. It determines the amount of energy required to maintain thermal comfort. One of the best options for saving energy in retrofitting or new building projects is through designing the building envelope in an energy conscious way. Energy simulations, if well-validated, can help us to correctly apply design strategies to achieve considerable energy-savings [4,5]. These strategies can be beneficial for both the refurbishment of existing buildings and the decision making during the preliminary design stage of new buildings. The most effective strategies contributing in energy-saving of building design, however, are those applied before construction [6].

The main objective of this study is to assess the role of building envelope design strategies on reducing the energy consumption of high-rise office buildings in temperate climates. Therefore this study aims to answer to the following questions:

- Which envelope measures (or components) can influence the energy performance of high-rise office buildings in temperate climates more effectively?
- What are the energy-saving solutions for each design measure considering their effect on heating, cooling, lighting and overall energy consumption and which one perform better among others?
- To what extent would the combination of envelope strategies provide energy-saving?

For this purpose an existing tall office building is selected as a typical high-rise building in the Netherlands and the energy usage pattern prior and after refurbishment is compared through a computer simulation. In this study, the energy efficiency indicator for the design strategies is the final energy use for heating, cooling and lighting. Verification of natural ventilation strategies requires a detailed investigation of air flow patterns. Therefore, a follow-up paper will investigate the effect of ventilation strategies via sky gardens, atria, cross ventilation and solar façades by means of CFD simulations, among others.

The envelope performance can be affected by three parameters: façade design parameters such as glazing type, window area and shading; building material properties such as thermal mass, insulation and airtightness; and site parameters such as building orientation and climatic features. The following section summarises the current literature regarding the optimisation of building design variables with the goal of energy-saving, with particular focus on envelope components.

2. An overview of previous studies

High levels of energy-saving usually can be achieved by an optimal combination of several measures. Therefore, in this section we tried to cover studies which offer a multi-objective optimisation approach for the envelope design. These solutions aim to improve thermal comfort in buildings while reducing the energy consumption.

In a parametric study, Eskin and Türkmen [7] investigated the effect of design variables such as insulation, thermal mass, external wall colour, shading, ventilation rate, window area and glazing type on the energy consumption of buildings in Turkey. A base case office building was developed for this parameter study and EnergyPlus was used to estimate the annual heating and cooling demand in four major cities with a different climate (Ankara, Istanbul, Izmir and Antalya). Finally the relative impact of different design parameters on building energy use were presented for each city. Although Eskin and Türkmen presented a holistic overview of

most of the envelope design parameters, occasionally the large number of selected design solutions prohibitively limited a deep investigation on some solutions such as shading.

Konstantinou and Knaack [8] studied the energy effect of building envelope components and installation systems on refurbishment of middle-rise residential buildings constructed in the 1960s. Refurbishment solutions were assessed with Capsol for two Northern European cities located in the Netherlands and Germany. The energy efficiency indicator was the heating demand, as it is the dominant energy demand for those climates. The proposed design approach reduced the energy demand for heating by 90%. However, the economic feasibility of these refurbishment strategies still needs to be investigated.

In search of the optimal balance between costs and energy benefits of refurbishment strategies, five types of dwellings in Belgium were selected by Verbeeck and Hens Maamari. Energy-saving measures included in this study were: insulation, window (frame and glazing type), heating system and renewable energy systems. With regards to the optimal balance between costs and benefits of energy-saving measures, investing in thermal insulation should be the first priority, while investing in high-performance glazing and heating systems are second priorities. Renewable energy systems such as solar collectors and PV-panels were found to be the least profitable among the proposed solutions.

Capeluto and Ochoa [10] used a simulation-based method to determine and rank energy-efficient retrofitting solutions in 13 urban centres from North to South Europe. Climate design strategies were defined through the use of psychrometric charts for each representative city and then translated into a conceptual façade module for evaluation through EnergyPlus. Finally, an energy ranking of each improvement and combinations of improvements was determined for a South-oriented façade for each climate. In Northern European cities, balanced ventilation with heat recovery, high-performance glazing and thick thermal insulation were the most influential solutions. For Central Europe, improved thermal insulation and glazing had the greatest impact on energy consumption reduction. In Southern Europe, where temperature and solar radiation intensity are higher, improved shading and glazing ranked higher.

Yıldız & Arsan [11] used a sensitivity analysis (Monte Carlo method) in line with EnergyPlus to determine the most influential design variables for energy consumption reduction of apartment buildings in hot-humid climates. 35 building parameters were selected from nine major groups and applied on an existing apartment building in Izmir, Turkey. The result showed that for heating air infiltration had the highest impact while for cooling the aspect ratio of the building and cooling set-point temperature played a key role. Furthermore, window area and glazing properties were found to be influential variables on building total energy consumption.

Tavares and Martins [12] used VisualDOE for the optimisation of design parameters of a public building in Portugal. Through a parametric study, the effect of the following design variables on annual heating and cooling energy were analysed: wall and roof type, window frame and glazing type, shading, HVAC system, infiltration rate, mechanical ventilation rate and temperature set-point. Taking the base case as a reference and optimising one variable at each step, they come up with an optimal solution that offers a considerable saving in energy by around 46% and 78% for cooling and heating respectively.

For the refurbishment of a residential high-rise building in Hong Kong, Cheung et al. [13] investigated the effect of six passive strategies on cooling energy and peak cooling load. TRNSYS was used as the simulation tool, and the variables investigated were: thermal insulation, thermal mass, glazing type, window size, colour of external wall and shading. For a hot and humid climate, they found that the optimal combination of passive strategies can save up to 31.4% in annual required cooling energy and up to 36.8% in peak cooling load.

Ng et al. [14] used a questionnaire survey to identify the feasibility of sustainable refurbishment methods for uplifting the energy performance of high-rise residential buildings in Hong Kong. For this purpose, 46 refurbishment measures were classified under 4 groups: building services, building envelope, building layout and renewable energy. They asked respondents (building owners and occupants) to indicate the degree of acceptability for each refurbishment measure. The result of the survey showed that improvements in the category of building services, such as lighting, appliances, mechanical ventilation and lifts, received higher attention from

the owners and occupants. However, building envelope strategies, such as high-performance windows and shading were not easily accepted. Additionally, they mentioned the initial and operational costs, service life and degree of intervention as factors that affected respondents' satisfaction to refurbishment strategies.

Among the passive design strategies for the building envelope, the double skin façade (DSF) technology has recently become a popular topic of study due to the complexity of thermal behaviour and air flow pattern involved in its design [15]. Glazing properties [16], type and position of shading devices [17,18], structure and depth of cavity [19,20] and size of air openings [21] are identified as parameters affecting the thermal and energy performance of buildings with DSFs. According to Barbosa and Ip [15] finding the optimal combination of glazing type is a key element for the design of naturally ventilated buildings with DSFs. In order to achieve a higher air flow rate, it is essential to increase air temperature in the cavity. The application of single-glazing (instead of double-glazing) for the inner layer allows for higher solar transmittance; improving natural ventilation through the stack effect in the cavity. Vice a versa, double-glazing with higher thermal insulation is better to be placed at the inner layer to reduce heat transfer through the façade.

The location of blinds within the cavity has significant influence on air temperature and ventilation rate. The optimal position of blinds within the cavity was investigated by Gratia and De Herde [18]. They found that placing the blinds close to the inner layer led to higher heat transfer from the cavity into the room; hence higher cooling demand. When blind were placed in the middle of the cavity, they not only provided shading but also enhanced the air circulation on two sides. Considering the influence of shading control strategies on visual comfort and energy demand of office buildings in Seoul, Yun et al [22] suggested a blind slat angle of 0° is better in winter, in case when there is no need for glare protection. However, in summer a blind slat angle of 30° is the optimal configuration for energy-saving and glare control.

Radhi et al. [19] performed a parametric analysis in order to assess the impact of different alternatives such as the cavity depth on reducing the cooling energy in a fully-glazed building with a DSF system located in hot arid climate of the UAE. They integrated building energy simulation with computational fluid dynamics analysis to establish and develop geothermal models. The results showed a reduction in heat transfer rate when the cavity depth reduced due to higher air velocity. However, surface temperature of the elements and solar heat gain increased with shorter cavity depth. Finally, they suggested a cavity depth between 70 and 120 cm can provide a balance between heat transmission and solar gain.

Ochoa et al. [23], finally, used a combined design optimization method to find the optimum window sizes in the four main orientations by optimizing simultaneously for high visual comfort and low energy consumption. Building computer simulations performed on a hypothetical office room with a single external wall and a double-pane clear glass window ($U\text{-value} = 1.7 \text{ W/m}^2\text{K}$). For normal office tasks, the standard illuminance target level of 500 lx was defined for electric lighting requirements. The results of this study determined the optimum window sizes for different orientations as following: for North: 50-70% WWR, for South: 60% WWR, and finally for East and West: 50-60% WWR. However, it must be noted that shading elements are excluded from window design with the aim to make the optimization process less complex. Therefore the optimum window-to-wall ratio might be different when adding shading elements or using a different glazing or façade type.

3. Methodology

The overall methodological scheme of this research is presented in Fig. 1. This figure shows the different steps we took in the study. The subsections afterwards go into the steps more deeply.

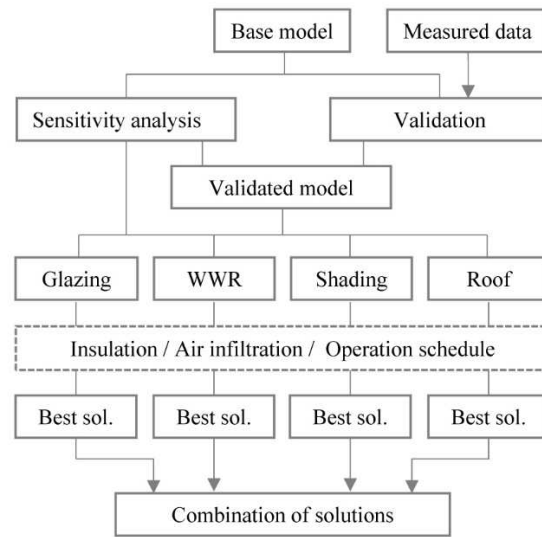


Fig. 1. Methodological scheme of research

3.1. Reference building description

The case study concerns the building of the Faculty of Electrical Engineering, Mathematics and Computer Science (EWI) of Delft University of Technology. It is located in Delft, a city in the temperate maritime climate of the Netherlands. The Faculty of EWI has three main buildings, a high-rise office building with the lower two storeys reserved for educational facilities, a low-rise educational building and a high-voltage lab. Since this study aims to define energy-saving solutions for the envelope design of tall office buildings, only the high-rise building will be investigated. From the total floor area of this 21-storey building, only the first two levels have a different layout while all the upper floors have an identical floor plan with cellular offices. The building has a rectilinear narrow plan with cellular offices along the façade and a corridor in between. Its main façades have an East respectively West orientation, as shown in Fig. 2.

The construction of the EWI building dates back to the 1960s when the development of double-skin façade technology was in its infancy and when building regulations had a limited energy scope. The energy consumption of this building, therefore, is relatively high (204 kWh/m^2) due to a high infiltration rate and high heat transmission through a low-performance façade. The building's envelope is built with a double skin façade (DSF). The DSF consists of single-pane tinted glass with a steel frame for the outer leaf and single-pane clear glass in a fixed window with wooden frame for the inner leaf and an air cavity between the two layers. The 95 cm cavity of the facade is horizontally continuous along the length of the facade, but vertically segmented at each floor. The cavity is accessible from two plant rooms at the ends of the corridor. Electric Venetian sun blinds are installed in this cavity in close distance to the external leaf; they can be controlled manually by the occupants.

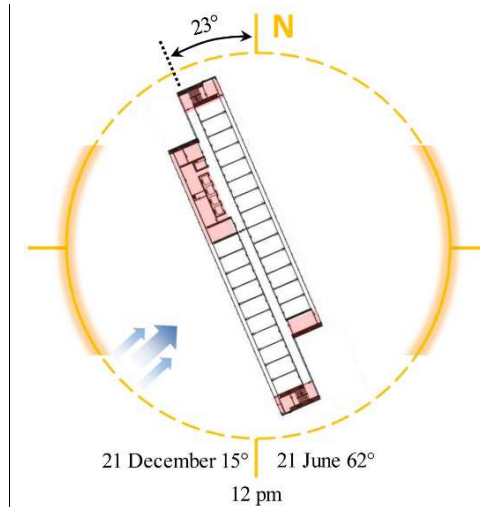


Fig. 2. A typical office floor plan and the orientation of building

In summer, the cavity in the façade is ventilated with outside air but for the majority of the year the air inlets are kept closed to minimise heat loss in cold weather. The fresh air is brought in from the centre of the façade and sucked out with the help of fans at the ends of the cavity's corridor. It means fresh air travels a long distance before being exhausted. The ventilation for the offices is separated from that of the cavity. The entire building is ventilated mechanically. Ducts in the façade cavity bring in fresh air for the office rooms. The stale air passes through openings in the dividing walls and is extracted in the corridor. The air flow diagram is presented in Fig. 3.

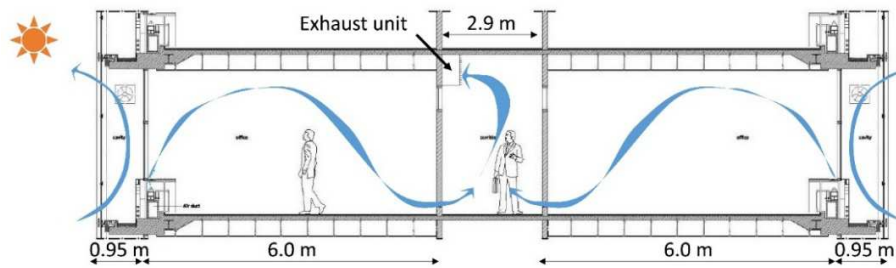


Fig. 3. Air flow in the office area

3.2. Climate data

The EWI building is located in Delft, a city with a temperate maritime climate in North-West Europe (Latitude $51^{\circ} 59' N$ and Longitude $4^{\circ} 22' E$). The climate is influenced by the North Sea and the Atlantic Ocean, with cool summers and mild winters. Two dominant climate features here are precipitation and wind. Rainfall is distributed relatively evenly throughout the year with a slightly dryer period from April to September. In fall and winter strong Atlantic low-pressure systems can bring strong winds which cause uncomfortable weather. Winds are omnidirectional but the predominant wind direction is South-West and the annual average wind speed is around 4.3 m/s.

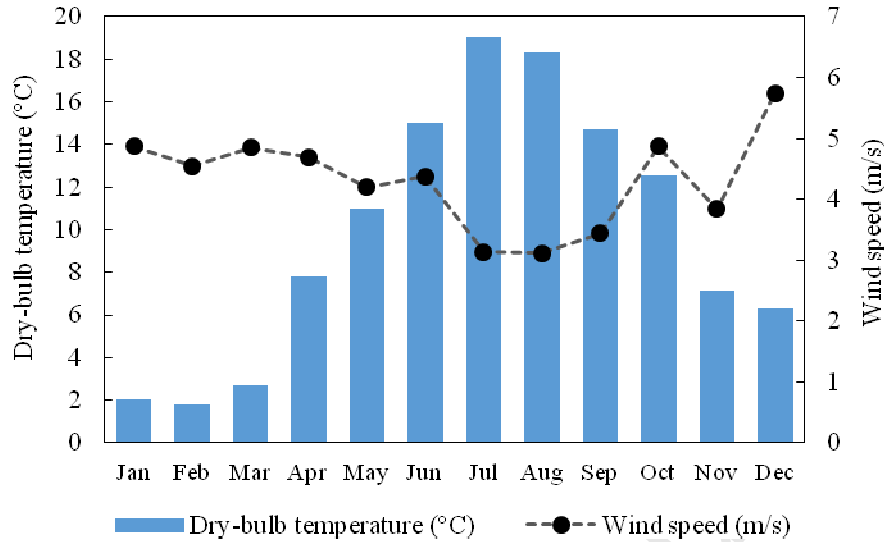


Fig. 4. Mean monthly values of dry-bulb temperature and wind speed at Rotterdam Airport for the year 2013

Detailed energy consumption figures of the EWI building were collected for the year 2013. Climate data of Delft was not available for the year 2013. For this reason the performance of the building was simulated using 2013 weather data from the nearby KNMI weather station at Rotterdam-The Hague Airport (6.5 km South-East of the location).

3.3. Simulated building model

The main objective of this study is to assess the role of building envelope design strategies on reducing the energy consumption of typical high-rise office buildings in temperate climates. For this purpose, the high-rise part of the EWI building is selected as a typical case building and the energy usage pattern prior and after the refurbishment is compared through a computer simulation. The DesignBuilder interface version 3.4 for EnergyPlus is used as a building energy performance simulation tool to create the model (see Fig. 5). DesignBuilder is a validated tool that has been passed Building Energy Simulation Tests (BESTest) according to the EN ISO 13790 standard (2008) for the calculation of energy use for space heating and cooling and the ASHREA standard 140 (2011) for building thermal envelope and fabric loads.



Fig. 5. 3D model of the EWI building developed in DesignBuilder

The real building properties and real climate data were used for making the simulation model. The properties of the construction materials used in this model are summarised in Table 1. In order to cope with uncertainties related to model inputs, a sensitivity analysis (SA) was set up. SA consists of testing a variable (input) in order to see its effect on the building performance (output) [24]. Therefore, with regards to uncertain input parameters, different quantities of inputs were simulated and the variation was observed. The results of SA are presented in Table 2. A large number of computer simulations helped us to have a better understanding of the relevant variables and their degree of influence on the building's energy consumption.

Table 1

Construction details of existing building

| | |
|-------------------|---|
| Floor and ceiling | Vinyl sheet 3 cm, concrete 10 cm, air gap 30 cm, gypsum board 2 cm |
| Roof | Uninsulated flat roof; asphalt 1 cm, concrete 10 cm, air gap 30 cm, gypsum board 2 cm |
| Side walls | Reinforced concrete shear wall 100 cm (end sides of the building) |
| Partitions | 10.5 cm brick plastered on both sides with white colour |
| windows | DSF: outer layer: single-glazed tinted glass (10 mm); inner layer: single-glazed clear glass (10 mm) |
| Cavity | 95 cm corridor type cavity (horizontally continuous but vertically segmented at every floor) and naturally ventilated in summer with the help of two exhaust fans |
| Window frame | Outer: Aluminium; Inner: Wood |
| Shading | Manually operated Venetian blinds inside the cavity |
| HVAC system | Hot water radiator, mechanical ventilation (supply and extract) |

When performing SA, some variables could influence building energy consumption more than others. For optimization of building energy performance, variables with high-sensitivity should be targeted [25-26]. The result of the SA gave us some clues about the building parameters which needs to be more investigated for energy-saving matter. For example, it showed that building loads is highly responsive to changes in the infiltration rate (44.2 kWh/m²) and glazing type (15.6 kWh/m²), so they should be in the first priority for the envelope refurbishment. Additionally, there are areas for the improvement of shading and the operation of external vents. For instance, using indoor blinds (base model) have relatively the same effect on the total building energy consumption as no shading device; hence, there is a need for a more in-depth energy analysis on different shading strategies in order to find the optimum solution. On the other hand the effect of some parameters such as heating and cooling set point temperature, occupancy schedule and miscellaneous equipment found to be negligible.

Table 2

Sensitivity analysis of building parameters

| Building parameter | Unit | Values | Max. output variation (kWh/m ²) |
|-----------------------------------|-----------------------|--|---|
| Infiltration | ac/h | 0.7, 1.5, 2* | 44.22 |
| External wall insulation | W/m ² K | 0.25 ^a , 0.37 ^b , 2.22 ^{c*} | 1.87 |
| Roof insulation | W/m ² K | 0.15 ^a , 0.37 ^b , 1.91 ^{c*} | 3.16 |
| Heating set point temperature | °C | 20, 21*, 22 | 0.33 |
| Cooling set point temperature | °C | 23, 24*, 25 | 0.18 |
| External vents operation schedule | --- | summer cooling*, off | 0.18 |
| Occupancy density | people/m ² | 0.11, 0.16* | 2.74 |
| Occupancy schedule | --- | weekends (open*, close) | 0.04 |
| Minimum outside fresh air | l/s- person | 4, 8*, 10 | 0.39 |
| Mechanical ventilation per area | l/s- m ² | 0.6, 1*, 1.6 | 0.45 |
| Mechanical ventilation schedule | --- | weekends (open*, close) | 1.52 |
| Miscellaneous equipment | W/m ² | 0, 5* | 0.14 |
| Glazing type (outer pane) | --- | clear, tinted* | 15.6 |
| Shading | --- | no shading, indoor blinds* | 1.16 |

*The base case settings of the reference model that led to the validated model; ^a best practice building; ^b recommended U-value by EURIMA (2007) for the Netherlands; ^c reference building (uninsulated)

3.4. Validation of the model

In order to test the accuracy of simulated model a validation was set up. Fig. 6 and 7 show a comparison of the measured and simulated energy use intensity (EUI) of the EWI building as far as it concerns total energy consumption and heating energy consumption. A simulation model is often defined as calibrated if it falls within a specific error margin. Maamari et al. [27] suggested error margin of 10 - 20% as an acceptable range for percentile difference (PD) between the simulation results and the measured data. This comparison of the monthly energy use intensity showed that the absolute value of the percentile difference was equal to or less than 15% for the majority of the months except for the summer months. Fig. 6 shows that in May, June and August the PD is more than 15% because the energy consumption for cooling is slightly underestimated by the simulation model during these months. At the EWI building, the air supply ducts are placed inside the cavity of the double-skin facade, as a result of which the chilled air is being heated along its way to the rooms. The efficiency of this cooling system is therefore low(er) and the electricity demand for cooling high(er) in the real building. The simulated model does not consider the extra cooling load due to the inefficiency of the distribution system, which explains the differences. Additionally, the energy use for heating accounts for more than 60% of the total energy consumption of the EWI building. As can be seen in Fig. 7, the simulated data are acceptably close to the measured data for heating energy consumption. As a result, the simulated model can be considered a sufficiently accurate base model for this study.

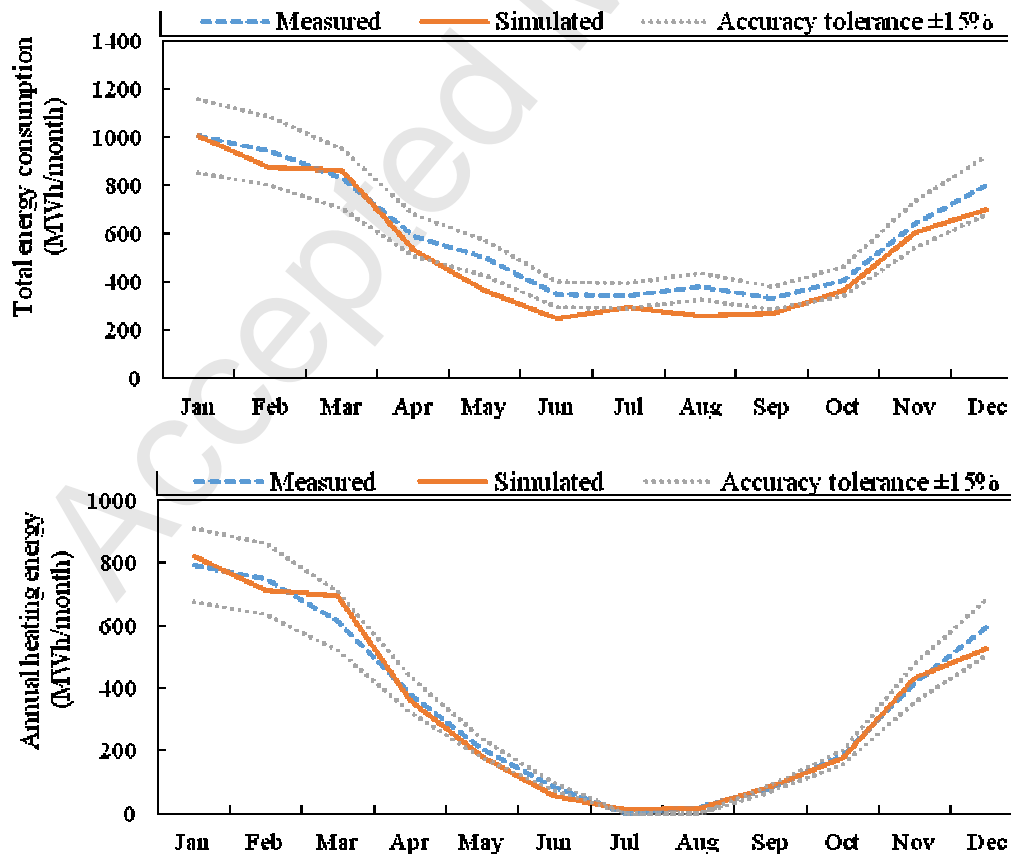


Fig. 6 and 7. A comparison of simulated and measured data considering the total energy and heating energy consumption of the EWI building for the year 2013

Using this model, a large number of computer simulations were run to evaluate the energy-saving potential of various design variables, as well as their combinations. As described in the following sections, retrofitting strategies for the building envelope grouped under 4 main categories were simulated using heating, cooling, lighting and total energy use as the efficiency indicator.

4. Results and discussion

Through the simulations, the effect of each strategy is quantified as the percentage of reduction or increase in the total energy usage compared to the reference model. However, to have a better understanding of how retrofitting strategies can contribute in energy-saving during the heating and cooling seasons, the effect of each strategy will be discussed additionally on heating, cooling and lighting energy demand. In some cases, in order to apply a new strategy, there is a need to change the floor plan configuration, which means a different floor area of the conditioned space. In order to make different strategies comparable, the total energy consumption per conditioned area was used as an indicator.

4.1. Glazing type

Façade performance depends to a large extent on the ability of glass panes to reflect, absorb or transmit solar radiation. When considering the influence of glazing type on daylight penetration, high-transmittance clear glass (high LT value) can lead to a reduction in energy consumption for lighting. This is also a preferable option for heating-dominant climates in which passive heat gains are highly desired (high g-value or SHGC). Solar heat gain coefficient (SHGC) is defined as a fraction of solar radiation that enters a building through the window. For hot climates, a type of glazing with low SHGC is needed to limit solar heat gains into the interior. Thermal transmission through a glass pane is another influential factor for envelope performance which can be reduced by choosing a low U-value.

The tinted single-glazed DSF of the EWI building is replaced by different types of glass and façade systems to investigate their potential for energy retrofitting. In terms of heating, DSFs with a double-glazed clear pane (Type G & H) achieved more energy-savings compared to a triple-glazed window, irrespective of the position of single or double-glazed panes. However, choosing a double-glazed pane for the inner layer (Type G) resulted in the highest amount of energy-saving for space heating. For the summer case, the energy figures showed that the optimum window type is the reference design and that the highest cooling demand occurs when using a single-glazed clear glass. The reference design window benefits from a tinted glass pane which reduces the solar transmission considerably compared to a clear glass pane. In terms of cooling load, the difference is up to 58% in relative value but less significant in absolute value (15 kWh/m²).

All of the solutions with clear glass have higher energy-savings for lighting compared to the original design. A deep air cavity (95 cm) in DSF forms a barrier against light transmittance, thus increasing the need for artificial lighting. Considerable reductions in energy use for electric lighting can be achieved by using window types A, C and D compared to the base case. However, the selection of the most energy-efficient window strategy is not possible without considering the overall energy benefits that a window can provide for the building, thus considering heating, cooling and lighting.

Table 3

Simulation results obtained for different glazing type

| Glazing | Annual heating demand | Annual cooling demand | Annual lighting demand |
|---------|-----------------------|-----------------------|------------------------|
|---------|-----------------------|-----------------------|------------------------|

| type | Total heating (kWh) | Heating / conditioned area (kWh/m ²) | Percentile difference (%) | Total cooling (kWh) | Cooling / conditioned area (kWh/m ²) | Percentile difference (%) | Total lighting (kWh) | Lighting / conditioned area (kWh/m ²) | Percentile difference (%) |
|---------|---------------------|--|---------------------------|---------------------|--|---------------------------|----------------------|---|---------------------------|
| Type A | 4192952 | 216.7 | 4.0% | 500114 | 25.8 | -58.0% | 428658 | 22.1 | 35.9% |
| Type B | 4940923 | 255.4 | -11.5% | 384194 | 19.8 | -45.4% | 562911 | 29.1 | 15.9% |
| Type C | 3995955 | 206.5 | 8.5% | 447214 | 23.1 | -53.1% | 438709 | 22.7 | 34.4% |
| Type D | 3994633 | 206.5 | 8.6% | 302640 | 15.6 | -30.7% | 497627 | 25.7 | 25.6% |
| Type E® | 4062323 | 225.9 | ---- | 195051 | 10.8 | ---- | 622062 | 34.6 | ---- |
| Type F | 3781715 | 210.3 | 6.9% | 324183 | 18.0 | -39.8% | 565565 | 31.4 | 9.0% |
| Type G | 3578574 | 199.0 | 11.9% | 254995 | 14.2 | -23.5% | 569612 | 31.7 | 8.4% |
| Type H | 3651551 | 203.0 | 10.1% | 261262 | 14.5 | -25.3% | 572911 | 31.8 | 7.9% |

Glazing description

| | Solar transmittance | U-Value (W/m ² -K) |
|--|---------------------|-------------------------------|
| Type A. [Sgl: Clr 10mm] | 0.74 | 5.67 |
| Type B. [Sgl: Tinted 10mm] | 0.30 | 5.67 |
| Type C. [Dbl: Clr 6mm/6mm air /6mm] | 0.60 | 2.40 |
| Type D. [Trp: Clr 6mm/6mm air/6mm/6mm air/6mm] | 0.46 | 1.71 |
| Type E. (Reference) DSF: inner pane: [Sgl: Clr 10mm]; outer pane: [Sgl: Tinted 10mm] | 0.22 | 1.48 |
| Type F. DSF: inner pane: [Sgl: Clr 10mm]; outer pane [Sgl: Clr 10mm] | 0.55 | 1.48 |
| Type G. DSF: inner pane: [Dbl: Clr 6mm/6mm air/6mm] - outer pane: [Sgl: Clr 10mm] | 0.44 | 1.09 |
| Type H. DSF: inner pane: [Sgl: Clr 10mm] - outer pane: [Dbl: Clr 6mm/6mm air/6mm] | 0.44 | 1.09 |

The result of the simulation for the total energy-saving by the application of different glazing types and systems are presented in Fig. 8. The graph shows that a double-skin façade type with double-glazed clear glass for the inner pane and single-glazed clear glass for the outer pane (Type G) results in the highest energy-savings: by around 7.5%. However, by switching the position of two layers (Type H: double-glazed clear glass for the outer pane and single-glazed clear glass for the inner pane), less energy saved. The inner pane in air-conditioned DSF buildings is the place where the majority of heat transfer occurs due to higher temperature differences between the conditioned indoor space and unconditioned air in the cavity. Therefore double-glazed pane with higher thermal insulation is better to be placed at the inner layer in order to reduce the radiative and convective heat transfer into the building. Considerable differences in energy-saving can be found between using clear glass and tinted glass. In temperate climates with high heating degree days (HDDs) clear glass allows for relatively easy transmission of both heat and light into a building, thus reducing the energy need for heating and lighting. For this reason, single-glazed clear glass even performed better than the reference design: a DSF with two layers of 10 mm glass (outer: tinted; inner: clear) and 95 cm air cavity in between.

These results were obtained for a high-rise case-building with North-East and South-West façade fully glazed and with high infiltration rate and no additional thermal insulation. Changing the orientation of the windows may influence the energy-savings of the glazing types in a different way. However, the aim of this study is to assess envelope strategies for the existing building and therefore the orientation of building was not changed.

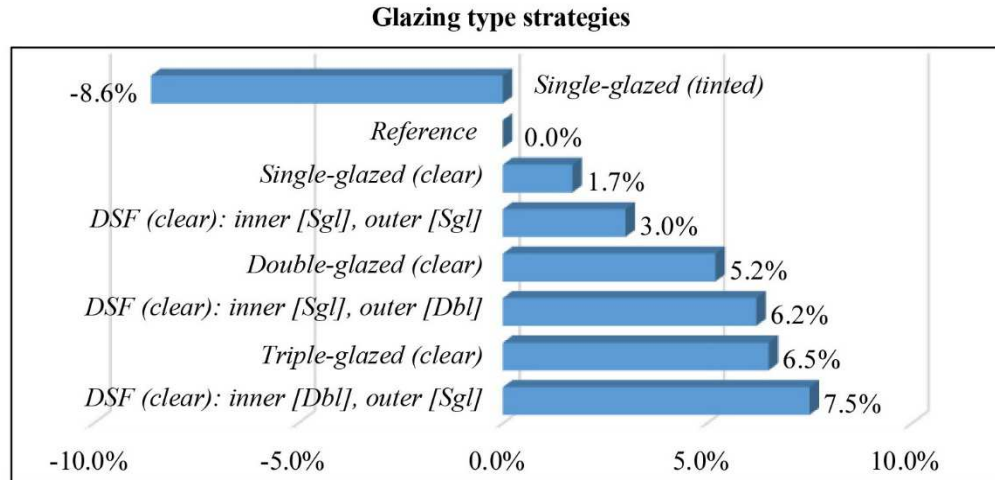


Fig. 8. The effect of using different glazing type on the percentage of total energy-saving

4.2. Window-to-wall ratio

The effect of window size on building energy consumption is investigated for different values of window-to-wall ratio (WWR). The North-East and South-West facing façades of the EWI building are fully glazed, while the other façades are made from 1 m of reinforced concrete and are designed to carry the lateral loads. In order to test the impact of window size, the outer pane of the DSF is subjected to modification while the inner pane is kept unchanged. While a WWR of 100% represents the reference design, three other values (80%, 50% and 30%) were also simulated. Except the reference model that is fully glazed, for other values of WWR the external wall that replaces the glass is supposed to be uninsulated similar to the roof conditions at this building. Therefore the opaque part of the façade is considered to be made from 20 cm brick wall with no insulation (U -value = $2.22 \text{ W/m}^2\text{K}$).

Table 4

Simulation results obtained for different window-to-wall ratio

| WWR | Annual heating demand | | | Annual cooling demand | | | Annual lighting demand | | |
|--------|-----------------------|--|---------------------------|-----------------------|--|---------------------------|------------------------|---|---------------------------|
| | Total heating (kWh) | Heating / conditioned area (kWh/m ²) | Percentile difference (%) | Total cooling (kWh) | Cooling / conditioned area (kWh/m ²) | Percentile difference (%) | Total lighting (kWh) | Lighting / conditioned area (kWh/m ²) | Percentile difference (%) |
| 30% | 4040547 | 224.6 | 0.5% | 154228 | 8.6 | 20.9% | 658280 | 36.6 | -5.5% |
| 50% | 4043043 | 224.8 | 0.5% | 165214 | 9.2 | 15.3% | 646698 | 35.9 | -3.8% |
| 80% | 4057811 | 225.6 | 0.5% | 182546 | 10.1 | 6.4% | 630553 | 35.0 | -1.3% |
| 100% ® | 4062323 | 225.9 | ---- | 195051 | 10.8 | ---- | 622062 | 34.6 | ---- |

The simulation results showed that for lower values of WWR, a higher percentage of energy-saving is achieved for both cooling and heating; meanwhile, energy use for electric lighting increased slightly compared to a fully glazed façade. In absolute values the differences were not significant. Since the external wall that replaces the glass has no thermal insulation and heating is the dominant type of energy consumed in this climate, replacing the glazed area with an uninsulated opaque façade element has limited energy benefits for the building. When the external wall that replaces the glass is not insulated, the maximum saving of total energy consumption is around 0.4%. Generally, a lower WWR is more beneficial in reducing the heat transmission through the glazed area but on the other hand limits daylight penetration and solar heat gains in winter. However, transmissions seems to be the more important factor in this case.

For the next step, the effect of different values of WWR were simulated again by improving the thermal insulation properties of the external wall that replaces the glass. For a well-insulated external wall (U -value = $0.25 \text{ W/m}^2\text{K}$), the maximum energy-saving improved to about 2.8% for a WWR of 30%. Increasing the WWR to 50% and 80%, resulted in a lower energy-saving of about 2.1% and 0.7% respectively.

As mentioned previously, a single-glazed tinted window has lower energy performance than a double-glazed clear glass window. The last modification to the existing facade was, therefore, performed by replacing the glazing type to type G from the previous section, which had the best thermal performance, while keeping the external wall well-insulated. Surprisingly, high (100%) or low (30%) values for WWR lead to less energy-saving. This means that for a high-performance envelope (low U -values for opaque parts and for glazing) on office buildings in a heating dominant climate, energy-saving is highest when the WWR is around 50%, which is the right balance for reducing heat transmission and increasing solar heat gains in winter. Generally, our findings are in good agreement with the result of Ochoa et al. [2]. They found the optimum WWR for East and West orientated windows (double-pane clear glass) between 50-60% for a hypothetical office room in a temperate climate.

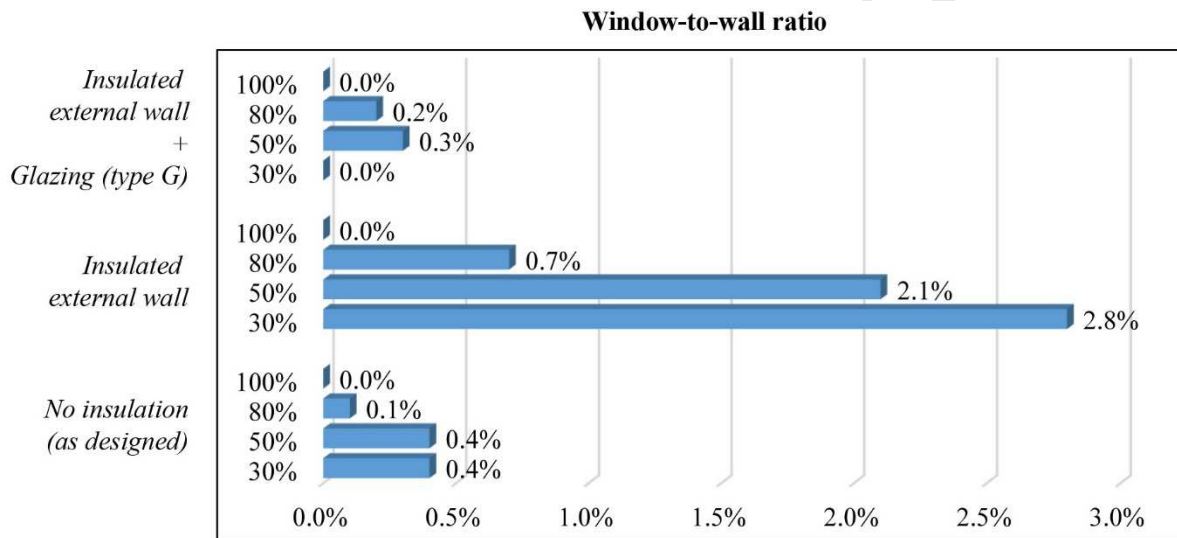


Fig. 9. The effect of different WWRs (Y-axis) on the percentage of total energy-saving presented in three scenarios:

4.3. Shading

The admittance of daylight and solar radiation has quite a significant influence on the energy consumption of buildings with a high percentage of window-to-wall ratio. Appropriate shading can play an important role for saving energy for cooling the building in summer. In order to have a high-performance shading strategy, it is important to provide a balance between easy access to view and daylight from one side and heat gain or glare control from the other side. Shading can be achieved by a wide range of building components including interior or exterior elements such as blinds, louvers, overhangs, side fins, and balconies. Another way to control sunlight without using blinds or external shading devices is the application of electrochromic glazing (switchable glass). Electrochromic glazing is an electronically tintable glass that can control glare and overheating.

Simulation results for 8 shading strategies (including the reference design) and a scenario with no shading device is presented in Table 5. During the winter, from a thermal standpoint, shading might be unfavourable. In climates where the dominant energy usage is heating, winter radiation entering through the windows can contribute to passive solar heating positively. It can be seen from the simulation results that no shading is the best option with 2.8% saving of total energy use compared to the reference case. No shading allows easy transmittance of light and solar energy into the building which leads to around 28% saving on electric lighting

besides 0.5% saving on heating energy. All the other shading strategies negatively affect the heating demand of the building.

Table 5

Simulation results obtained for different shading strategies

| Shading | Annual heating demand | | | Annual cooling demand | | | Annual lighting demand | | |
|---------|-----------------------|--|---------------------------|-----------------------|--|---------------------------|------------------------|---|---------------------------|
| | Total heating (kWh) | Heating / conditioned area (kWh/m ²) | Percentile difference (%) | Total cooling (kWh) | Cooling / conditioned area (kWh/m ²) | Percentile difference (%) | Total lighting (kWh) | Lighting / conditioned area (kWh/m ²) | Percentile difference (%) |
| S.1 | 4041478 | 224.7 | 0.5% | 210467 | 11.7 | -7.3% | 448354 | 24.9 | 27.9% |
| S.2 | 4092286 | 227.5 | -0.7% | 179003 | 9.9 | 8.2% | 589073 | 32.7 | 5.3% |
| S.3 | 4122161 | 229.2 | -1.4% | 171848 | 9.5 | 11.9% | 594102 | 33.0 | 4.5% |
| S.4 | 4174134 | 232.1 | -2.7% | 154634 | 8.6 | 20.7% | 610293 | 33.9 | 1.9% |
| S.5 ® | 4062323 | 225.9 | ---- | 195051 | 10.8 | ---- | 622062 | 34.6 | ---- |
| S.6 | 4176592 | 232.2 | -2.7% | 134027 | 7.4 | 31.3% | 555235 | 30.9 | 10.7% |
| S.7 | 4079531 | 226.8 | -0.4% | 188654 | 10.5 | 3.3% | 634727 | 35.3 | -0.2% |
| S.8 | 4124334 | 229.3 | -1.5% | 172986 | 9.6 | 11.3% | 516679 | 28.7 | 16.9% |
| S.9 | 4153924 | 230.9 | -2.2% | 160103 | 8.9 | 17.9% | 533717 | 29.7 | 14.2% |

S.1 Without shading; S.2 Overhang (1m); S.3 Overhang+side fins (1m); S.4 Louver+overhang+side fins (1m); S.5 Reference: Blind (inside); S.6 Blind (outside); S.7 Balcony (2m)+blind (inside); S.8 Electrochromic glazing; S.9 Electrochromic glazing+overhang (1m)

Generally, switchable and adjustable shading devices showed better performance compared to fixed external sun-shading strategies, since the operation of them is set based on the occupancy schedule. It means that shading operation is on only when the building is occupied (7:00 am to 19:00 pm). Electrochromic glazing has the second best overall energy performance among the shading strategies with considerable energy-savings for lighting (16.9%) and cooling (11.3%) and a total energy-saving of around 1%. Shading the envelope with 1 m of projected overhangs can slightly improve the energy consumption (0.3%), but in combination with electrochromic glazing, the effect was negative, reducing the performance from 1% to 0.5%.

For two shading strategies, blinds with medium reflectivity slats are adjusted within 5 cm distance from the outer pane. The angle of the blind slat is set on 45° and the operation of them is set based on the occupancy schedule. Locating the blinds inside the DSF cavity lets heat being transmitted into the cavity but the blinds might cut-off daylight penetration into the interior. For this reason, relocating the blinds to the outside (with the same distance from the outer pane) slightly reduces the overall energy consumption by 0.2%. The results show that for lighting and cooling, placing the blinds outside can save more energy than placing them inside the cavity, but in regard to heating indoor blinds are a better solution. Finally, integrated external shading strategies by the application of louvers, overhangs, balconies or side fins have a negative impact, i.e. they increased the total energy consumption by 0.1% to 0.8%.

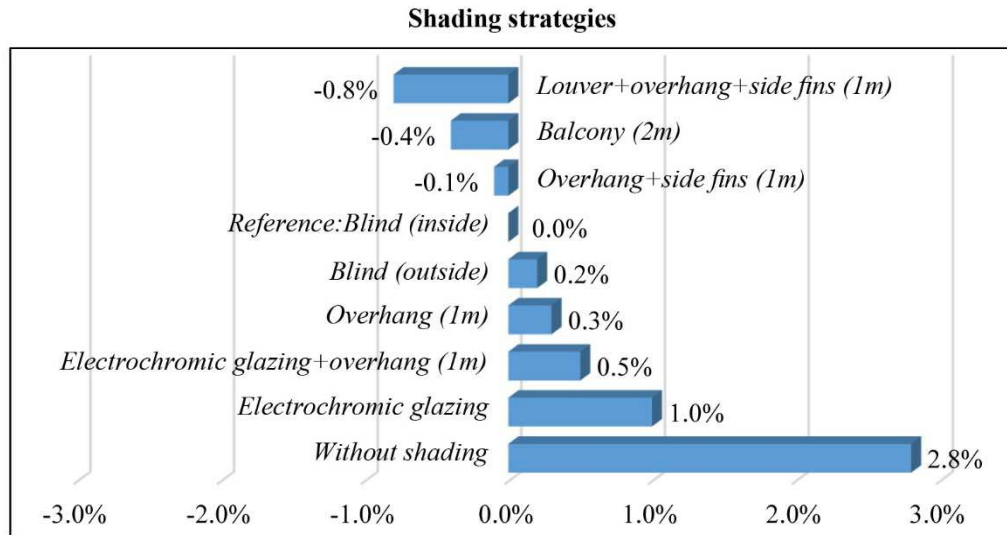


Fig. 10. The effect of shading strategies on the percentage of total energy-saving

The important role of the DSF cavity (95 cm) in providing a constant shading for the building interior should be emphasised here. Surprisingly, when there was no shading selected, cooling demand just slightly increased by about 7.3%. Furthermore, selection of a single-glazed tinted glass as outer glass pane (reference design) limited solar radiation transmittance into the building interior. Therefore, a deep cavity in combination with tinted glass simultaneously limit the solar heat gain into the EWI building even when there is no shading device present. Therefore, changing the glazing type might influence the performance of the shading devices.

For the next step, therefore, the type G glazing from the previous section is selected for the base case and the impact of different shading strategies re-simulated, the results are shown in Fig. 11. The results of these simulations for a high performance double-skin façade showed less energy benefits coming from using shading devices. For the majority of shading strategies the negative effect of shading during the heating period is higher than the positive effect during the cooling period. Shading strategies like blinds (outside), electrochromic glazing and integrated external shadings increased the heating load more than other strategies. In case of outdoor blinds, despite 4.9 kWh/m² of energy-saving for cooling and 7.6 kWh/m² for electric lighting, a considerable increase of the heating load (11.1 kWh/m²) reduces the overall energy benefits to about a mere 0.4%. However, when there is no shading system in place, energy-saving increased by 4.3%. Despite the positive energy benefits achieved through removing a shading device, the excessive amount of daylight may affect discomfort glare for the occupants. This often leads to increased dissatisfaction especially for the period of high solar radiation intensity. Changing the shading operation schedule to only operate in summer, not only can avoid glare but it might provide saving of cooling energy without increasing the heating demand in winter.

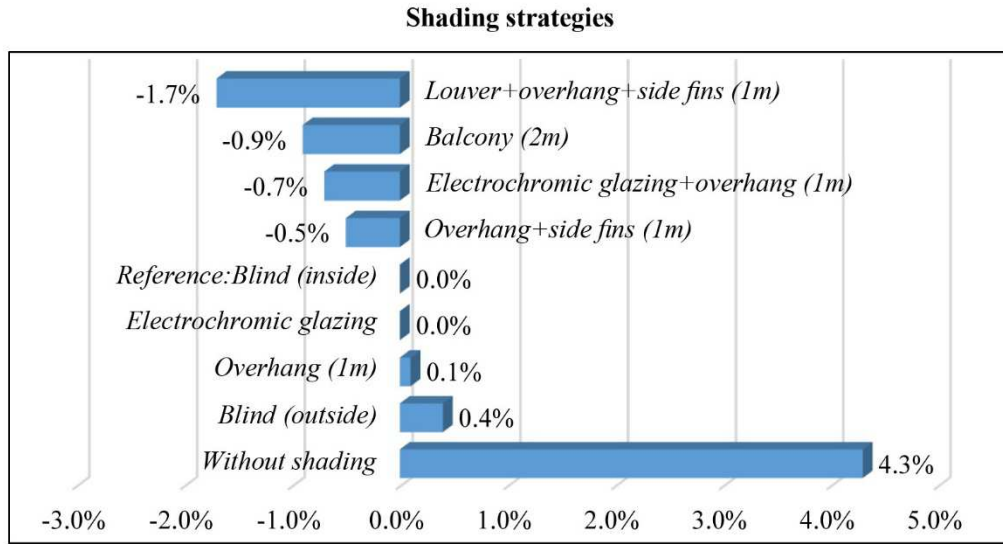


Fig. 11. The effect of shading strategies with a high performance window (type G) on the percentage of total energy-saving

Therefore a summer operation schedule is set for all adjustable shading strategies and the impact of different shading strategies re-simulated with keeping the type G glazing, the results are shown in Fig. 12. When the operation schedule only includes summer use, the energy benefits coming from using adjustable shading devices are quite different. The results showed using outdoor blinds is the best shading solution led to an overall energy-saving by about 1.9%, followed by electrochromic glazing ranked as the second best with 1.2% energy-saving. When there is no shading system in place, more cooling energy is needed in comparison with the reference case that caused the overall energy to be increased by 1.3%. Finally, the fixed external shading strategies showed considerably a lower energy performance compared to the adjustable shading strategies.

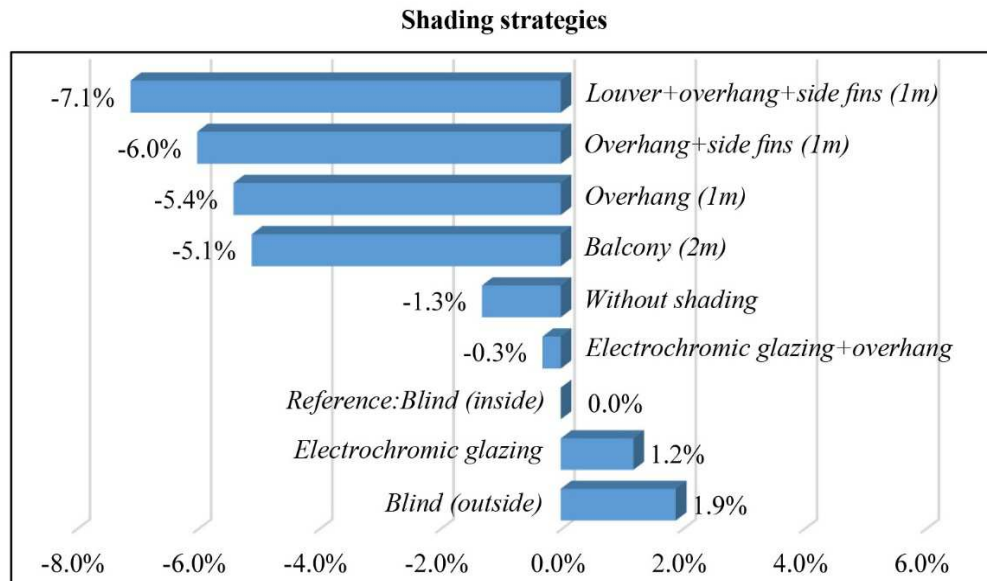


Fig. 12. The effect of shading strategies when the operation schedule only includes summer use on the percentage of total energy-saving (with glazing type G)

4.4. Roof

In high-rise buildings, compared to the vertical surfaces, only a small percentage of the building envelope is allocated to the roof. The EWI building is no exception but due to a big 2-storey attachment, the roof surface is relatively a bit larger. Since the building has no thermal insulation, a green roof might reduce the energy consumption of the building by among others adding thermal mass to the roof. The evaporative cooling effect of a green roof may be beneficial in summer but detrimental in winter. The whole roof area is therefore covered by an extensive green roof and the energy usage prior and after the application of green roof is simulated. The properties of the simulated green roof is described in Table 6.

Table 6

Green roof properties

| Green roof parameter | Value |
|-----------------------------------|-------|
| Leaf area index (LAI) | 5 |
| Height of plants (m) | 0.1 |
| Leaf reflectivity | 0.22 |
| Leaf emissivity | 0.95 |
| Minimal stomatal resistance (s/m) | 180 |

The results of the simulation showed that a 10 cm green roof can provide some energy-saving for cooling and for heating by around 1.6% and 1% respectively. In comparison with a green roof a well-insulated roof (U-value: 0.15 W/m²-K) resulted in greater overall energy-savings. Adding a green roof to a well-insulated roof hardly influences heating energy consumption, showing just a reduction in cooling energy consumption by 0.1%.

Table 7

Simulation results obtained for roof strategies

| Roof | Annual heating demand | | | Annual cooling demand | | | Annual lighting demand | | |
|------|-----------------------|--|---------------------------|-----------------------|--|---------------------------|------------------------|---|---------------------------|
| | Total heating (kWh) | Heating / conditioned area (kWh/m ²) | Percentile difference (%) | Total cooling (kWh) | Cooling / conditioned area (kWh/m ²) | Percentile difference (%) | Total lighting (kWh) | Lighting / conditioned area (kWh/m ²) | Percentile difference (%) |
| 1 | 4069714 | 226.3 | 1.0% | 194115 | 10.8 | 1.6% | 622568 | 34.6 | 0.0% |
| 2 | 3970393 | 220.7 | 3.4% | 196226 | 10.9 | 0.5% | 622568 | 34.6 | 0.0% |
| 3 | 3972018 | 220.8 | 3.4% | 196537 | 10.9 | 0.4% | 622568 | 34.6 | 0.0% |
| 4 @ | 4110193 | 228.5 | ---- | 197376 | 11.0 | ---- | 622568 | 34.6 | ---- |

1. Green roof (uninsulated roof); 2. Green roof (well-insulated roof); 3. Well-insulated roof; 4. Reference (no insulation)

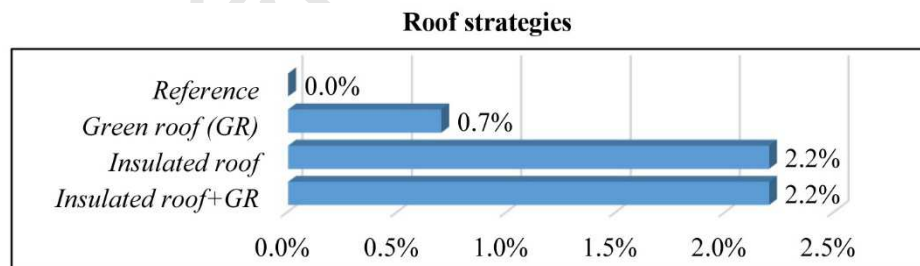


Fig. 13. The effect of roof strategies on the percentage of total energy-saving

4.5. Integration of envelope strategies

According to the results obtained from the previous analyses, an integrated design solution was defined. The final combination for the design of the envelope was selected based on the strategies that provided the highest energy benefits for the building. As a result, this combination might not correspond to an economically feasible envelope design for refurbishment of an existing building but it is expected to have a high energy-saving

potential. In Table 8 the final combination of building parameters and their relevant values for the integrated strategy are listed accordingly.

Table 8

The final combination of building envelope parameters

| | |
|--------------------------|---|
| Glazing type | DSF: inner pane: [Dbl: Clr 6mm/6mm air/6mm] - outer pane: [Sgl: Clr 10mm] |
| Window-to-wall ratio | 50% |
| Shading strategy | Blinds (outside) with summer operation schedule |
| External wall insulation | 0.25 W/m ² K |
| Roof insulation | 0.15 W/m ² K |
| Infiltration rate | 0.7 ac/h |

Comparing the results of the high-performance integrated design to the reference design, shows that the differences are quite significant. The combination of energy-saving measures reduces the total energy consumption by 42%, the heating demand by 64% and the energy use for electric lighting by 34%. However, replacing the tinted glass pane with a clear glass and lowering the amount of air infiltration resulted in a 40% increase of the cooling load. In terms of cooling load, although the differences are big in percentage, they are small in absolute value (6.8 kWh/m²). As the cooling energy demand is very limited compared to heating energy demand, this small increase does not have a significant effect on the total energy consumption and can be neglected. However, it is important to be aware of overheating inside the offices.

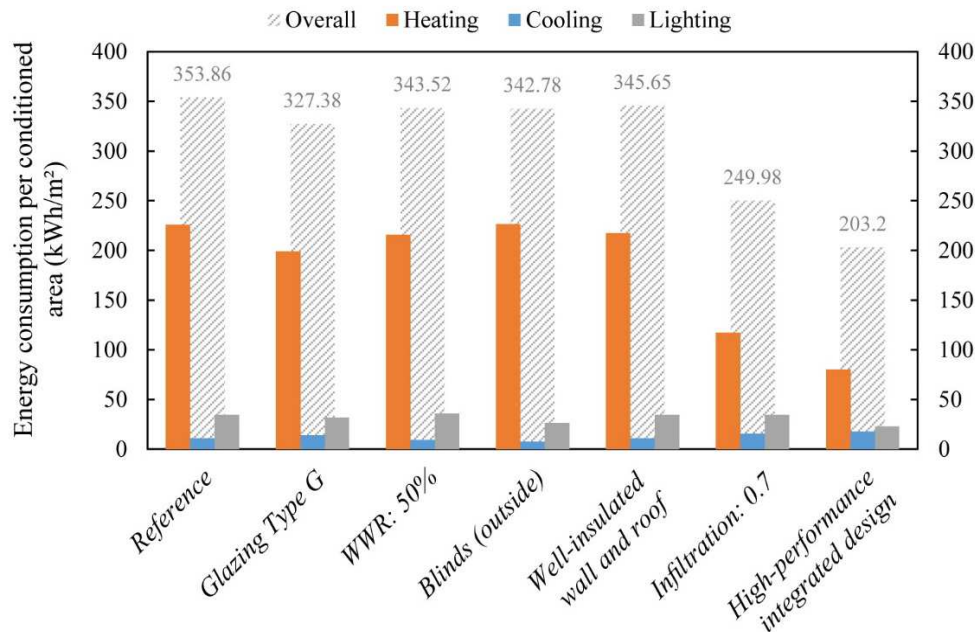


Fig. 14. Comparative energy analyses of the selected design options and the reference design

5. Conclusion

In temperate climates, the effect of envelope parameters on building energy consumption was assessed for an existing high-rise office building. Energy simulations in line with a sensitivity analysis defined 4 façade parameters with higher impact on building energy consumption; hence need more consideration for improvement. These measures were: glazing type, window-to-wall ratio, shading and roof strategies.

A large number of computer simulations were run to evaluate the energy-saving potential of various design variables, as well as their combinations. The main findings of this study are outlined as follows:

- Considering the glazing type we found that a DSF type with double-glazed clear glass for the inner pane and single-glazed clear glass for the outer pane results in the highest energy-savings.
- For a high-performance envelope (low U-values for opaque parts and for glazing), energy-saving is highest when the WWR is around 50%, which is the right balance for reducing heat transmission and increasing solar heat gains in winter.
- For heating-dominant climates in which passive heat gains are highly desired, adjustable shading strategies such as operable blinds and electrochromic glazing perform considerably better than fixed external shadings if a summer operation schedule set.
- In buildings with a DSF, for lighting and cooling, placing the blinds outside can save more energy than placing them inside the cavity, but in regard to heating indoor blinds perform slightly better.
- For a non-insulated roof, a 10 cm green roof can provide an overall energy-saving by around 0.7%. However, adding a green roof to a well-insulated roof hardly influences energy consumption.
- Finally, the integration of high-performance design solutions offers a considerable saving in energy by around 42%, 64%, and 34% for total energy, heating energy and electric lighting energy use respectively.

Energy-saving strategies for existing buildings are different from new buildings in that many of the design variables are fixed such as the building orientation. One of the limitations of this study, therefore, is that it does not provide energy simulations for all possible orientations. The main facades of the case building have an East respectively West orientation that is part of the boundary conditions in this research. However, our findings could provide a clear idea and a better understanding of the influential envelope design measures for energy consumption reduction of high-rise office buildings and their effect on cooling, heating and electric lighting in temperate climates.

Differences in specifications such as the building's properties beside the indoor condition settings are important parameters that define the performance and, thus, the effectiveness of design strategies. As a consequent, uncertainties related to simulation inputs are important to be considered prior to finalising the base model. In order to cope with uncertainties related to model inputs, a sensitivity analysis (SA), thus, is recommended to be carried out in line with energy simulations. This method helps to have a better understanding of the relevant variables and their degree of influence on the building's energy consumption.

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